Applied Mathematics and Computation 311 (2017) 47–57

Contents lists available at ScienceDirect

Applied Mathematics and Computation

journal homepage: www.elsevier.com/locate/amc

Coevolving allocation of resources and cooperation in spatial evolutionary games

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ARTICLE INFO

Keywords:
Evolutionary games
Co-evolution
Resource distribution
Prisoner's dilemma game

ABSTRACT

In this article, the co-evolution of resources and cooperation in spatial evolutionary games is studied. Existence of competition in nature and human society derives from the confrontation between the limit of resources and the infinity of demands. As a result, resource allocation is inseparable from various games, where resource acquisition depends on the outcome of games and the number of possessing resources would in turn affect the choice of game strategy. Here, by means of a concise and strategy-independent rule, limited resources are firstly involved into the evolution of prisoner's dilemma game (PDG) and three main results are obtained: (a) the coevolving resources in PDG can effectively promote the level of cooperation, and players with cooperative behavior are easier to possess resources; (b) in equilibrium, resources in the system approximately follow the power law distribution. A fraction of players would hold the most of resources but a considerable number of players lose almost all their property; (c) when the lowest guarantee of resources as a protective mechanism is assigned to each player, the level of cooperation can be further promoted. Moreover, an optimal value of the lowest guarantee can be found to inspire cooperative behaviors. The related microscopic system properties are studied and other social dilemmas as different kinds of representatives are also discussed.

1. Introduction

In nature and human society, the finiteness of resources always leads to the competition among individuals. As a result of competition, resource distribution presents tremendous unbalance and this kind of disequilibrium exists widely in various fields [1]. As a common example, to observe the income distribution all around the world, regardless of the level of economic development or social–political system, according to the international current measurement yardstick (Gini coefficient), the disparity of income distribution is constantly expanding over the past 30 years [2,3]. Simply put, the Matthew Effect that the rich get richer while the poor get poorer is more serious, and the unfair distribution has been an issue that is very much concerned in the contemporary society. By studying the microscopic mechanism of macro phenomena in complex systems and gaining insight to the relationship between resource allocation and competition, effective ways to improve the utilization of the limited resources could be discussed, that is an interesting topic attracting wide interest of researchers [4,5].

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http://dx.doi.org/10.1016/j.amc.2017.05.009
0096-3003/

Competition and cooperation are two typical biological behaviors in biology [6]. For survival and reproduction, the nature of organisms is to obtain as many resources as possible, that directly leads to competitive behaviors [7]. Meanwhile, cooperative behaviors are spontaneously generated from a competitive environment to maintain the overall interests of a group and resist the invasion of external races [8]. Evolutionary game theory, as a mathematical framework, is usually applied to study the emergence of reciprocal behavior of cooperation among self-interested entities in the context of Darwinian evolution [9]. Over the last few decades, evolutionary games have attracted extensive interest from various disciplines including physics, sociology, psychology, economics, and so on [10–14]. On the other hand, the development of network science in recent years provides the various theoretical models for the studies on transmission dynamics [15–17], control and synchronization [18–20], identification of communities [21,22], etc. Thereinto, the evolution of evolutionary game, based on different networked populations, such as lattices [23], small-world networks [24], well-mixed networks [25] and interdependent networks [26,27], etc., have been discussed.

In this article, we address the problem of coevolving allocation of resources and cooperation in spatial evolutionary games. As we know, in nature, the competition for more living resources is the instinctive selective process of organisms. In the previous studies, researchers mainly focused on the evolutionary dynamics and how to improve cooperative behaviors in the population. By means of additional abilities for game participants, the fraction of cooperation could be promoted, such as memory capability [28], teaching activity [29], aspiration-based partner switching [30], and risk attitude adaptation [31]. Meanwhile, some studies found specific population structures could be beneficial for altruistic behavior, for instance, the spontaneous emergence of interdependent network reciprocity can significantly promote the cooperation [26,27,32]. Moreover, in recent years, coevolutionary games have become a rising concern in this research field, where various coevolutionary rules, such as evolving teaching activity [33,34], population growth [35], dynamical interactions [36] and mobility of players [37,38], have been proposed and bountiful results are obtained [39,40].

Based on the above discussion, although some interesting results have been obtained, there are few studies to investigate evolutionary games from the view of resource allocation. In our work, limited resources are initially assigned to each player on average. The total quantity of resources in the population is fixed, but resources can be continually re-allocated with the process of evolution. We assume the resource allocation is related with the outcome of games, i.e., a winner in a round of game can get a certain amount of resources from the loser. Meanwhile, competition would also be influenced by the quantities of game participants' resources. The above assumption is accordance with the situation in reality, since a winner of game would generally obtain some additional resources as a reward and the loser would be deprived of certain right. And, players with more resources normally have a higher probability to win the competition. In our studies, based on a fairly concise and strategy-independent rule, the co-evolution of game strategy and resources is discussed. Specifically, we focus on three aspects. Firstly, we investigate the evolutionary dynamics and the statistical characteristics of the resource distribution in equilibrium. Secondly, we are interested in the effect of the coevolving resources allocation on cooperative behaviors. Thirdly, to take a reference from the social security system, the lowest guarantee of resources as a protective mechanism is designed to protect the vulnerable group in the population and the proposed dynamics is investigated. Besides, in order to discuss the universality of our results, snowdrift game as an additional case of pair-wise interaction and public good game as the representative of group interaction are implemented.

This article is organized as follows. In Section 2, the implemented game model and the related network structure are introduced. And, a strategy-independent coevolutionary rule is proposed. Next, we present main results and discuss their implications. Finally, a concluding remark is given.

2. Model

In this article, evolutionary games are implemented on a square lattice, the size of which is $L\times L$ with periodic boundary conditions. Each player on lattice has four links with its nearest neighbors, i.e., players only can interact with its four linked neighbors. The weak prisoner's dilemma game, as a revised version of PDG, is adopted in the following studies, where, for mutual cooperation, each cooperator can get a reward $R=1$; for mutual defection, each defector can get a punishment as $P=0$; and the temptation to defect, $T=b\,(1 < b \leq 2)$ as well as sucker's payoff, $S=0$. In spite of the simplification of PDG, the weak prisoner's dilemma game can describe all the related characteristics of PDG and be widely used in the previous studies [28,41]. In the initial phase, one of two strategies, i.e., cooperation or defection, is randomly assigned to each player on lattice with equal probability. At the same time, a basic unit of resource would also be averagely allocated to each game participant. The total resources in the population are $L\times L$ units, which would be assumed to a constant, i.e., limited resources in system only can be re-allocated among players but not increase or decrease.

During the process of evolution, based on the standard Monte Carlo (MC) simulation, game strategies and resources would co-evolve simultaneously on lattice. Firstly, a player x on lattice is randomly chosen to play the weak PDG one by one with its four linked neighbors, and it can obtain an accumulated payoff p_t^x at time t. Secondly, player y, which is one of the neighbors of player x, will be selected on random and play game with its own four neighbors to obtain the payoff p_t^y. Thirdly, player x propagates its strategy to player y with the probability given by the modified Fermi distribution:

$$W(x\to y)=\frac{r_x}{1+exp\left\{\left[p_t^y-p_t^x\right]/\kappa\right\}},\tag{1}$$